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(54) Title: CHANNEL BALANCING OF A WAVELENGTH DIVISION MULTIPLEXED OPTICAL SIGNAL

(57) Abstract: The invention relates to methods and arrangements for channel balancing of a wavelength division multiplexed optical signal. Channel balancing according to the invention is performed by using a resonator that provides a selection region in which a selected channel has a substantially increased power density relative to channels out of resonance. The selected channel is attenuated a desired amount, i.e. a desired amount of power is removed therefrom, by adjusting the properties of the selection region. In a preferred embodiment, attenuation is achieved by adjusting the selection region such that destructive interference is obtained for the selected channel in a fibre carrying the multiplexed optical signal.



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CHANNEL BALANCING OF A WAVELENGTH DIVISION MULTIPLEXED
OPTICAL SIGNAL

Technical field of the invention

The present invention relates to channel balancing in optical wavelength division multiplexed (WDM) systems or dense WDM systems (DWDM). More particularly, the present invention relates to methods and apparatus for controlling the power levels of individual wavelength channels within a WDM or a DWDM signal.

Technical background and related art

10 In order to increase the transmission capacity of optical fibre networks and communication links, wavelength division multiplexing techniques are often utilised. In WDM systems, a plurality of wavelength channels are transmitted through a single optical fibre (or possibly, other waveguiding means). Due to the nature of light, cross-talk between different wavelength channels is negligible and very high transmission rates can be achieved.

Although current optical fibres exhibit extremely low losses, optical repeaters are needed if transmission is carried out over long-haul transmission lines. Such optical repeaters typically comprise fibre amplifiers for amplifying the optical signal propagated by the fibre. The amplification in the amplifiers is normally slightly different for different wavelengths, i.e. for different channels within the WDM signal. Moreover, different wavelengths may experience different losses along the optical network. Therefore, the relation between the power levels of the individual channels is not preserved throughout the network.

It is often desirable to maintain a constant power distribution between the channels, or to maintain a constant signal-to-noise ratio between the channels. In

other cases, it can be desirable to maintain a certain power profile between the different wavelength channels in a WDM signal. To achieve this, it is necessary to introduce "gain equalisation", also known as channel balancing. A small variation between the channel powers at the transmitter can cause large variation between the channel powers at the other end. In general, the power levels of the different channels will change unpredictably as the signal propagates through the optical network. To overcome this problem, different approaches have been proposed.

A first suggestion was to utilise pre-equalisation of the channels. Pre-equalisation is a method where the WDM signal is conditioned prior to transmission through the network. Compensation is then introduced at the transmitter in order to allow for upcoming channel-specific losses in the network. However, this method has some serious drawbacks. The amount of pre-equalisation possible is limited and may not be enough for the intended purposes. Furthermore, there has to be communication back to the transmitter from the receiver. In particular, this approach is only feasible in point-to-point connections where the routing through the network is the same for every channel in the WDM signal.

To improve the channel balancing, it was proposed to equalise the channels at every amplifier stage. This could be done by demultiplexing the channels after each amplifier stage, then attenuating each channel separately, and subsequently multiplexing the channels back together for further transmission through the network. However, this approach required a very complex structure of hardware, and added tolerance penalties in the demultiplexing/multiplexing stages. For these reasons, this approach was not feasible for commercial use.

Alternatively, a multi-channel filter could be used. One example of such filter is an acousto-optic tuneable filter (AOTF). An AOTF uses an RF signal to attenuate

each channel independently of the others. However, the AOTF requires high amounts of driving power to balance more than a few (2-4) channels, and there is an increased tendency to cross-talk between the channels due to the
5 acousto-optic filtering. Consequently, the use of an AOTF is not feasible when trying to equalise a large number of channels in a DWDM signal.

Another method is to use carefully designed passband filters to equalise the channels. Since this method is
10 not tuneable, it is of minor importance in high-performance optical networks. Furthermore, fixed filters are believed to cause difficulties when used in connection with dynamic routing of channels, in which case it is not known in advance which way a certain channel will travel
15 through the network.

A recent effort towards channel balancing is disclosed in US-A-6 134 034. In that case, feedback from a receiver to a transmitter controls the power levels of individual channels before multiplexing the channels together. In essence, this is just pre-equalisation. As
20 mentioned above, serious problems are connected with such an approach. Firstly, the method is only feasible for point-to-point connections. If the network is constituted by a mesh, in which the channels can take any route, the principle does not apply. Secondly, and as mentioned
25 above, pre-equalisation is sometimes not enough. This is particularly obvious when it is not known at the transmitter which route each channel will take through the network.

30 Consequently, there is a need for new methods and apparatus for channel balancing that can allow any routing through the network, that can be located at any point in the network, and that dynamically equalise the power levels between channels according to any desired scheme.
35 Summary of the invention

A general object of the present invention is to provide channel balancing in WDM or DWDM optical systems

that eliminates or at least alleviates the problems associated with the prior art. This general object is achieved by methods, couplers and arrangements according to the appended claims.

5 Moreover, the present invention provides other features and advantages that will become apparent when the following detailed description of some preferred embodiments is read and understood.

 Accordingly, the present invention provides a
10 method, and an arrangement for performing the method, for channel balancing of a wavelength division multiplexed (WDM) optical signal, the method including the steps of identifying at least one channel, within said optical
15 signal, having higher than a desired power level; establishing a resonance to said channel, the resonance providing a selection region where said channel has a substantially increased power density relative to other
20 channels in the optical signal; and attenuating said optical signal by manipulating the selection region, the attenuation thereby being negligible for any channel out
of resonance but pronounced for the resonant channel.

 Hence, the channel balancing is performed directly upon the multiplexed optical signal without any actual demultiplexing, in a conventional context, of the same.
25 Instead, one channel is singled-out in a selection region while other channels may remain multiplexed in the optical signal. Light from the selection region is fed into the multiplexed optical signal, and by adjusting the properties of the selection region, it is possible to apply
30 desired effects on the channel. For example, the channel that is singled-out by the selection region can easily be attenuated virtually without affecting other channels within the optical signal.

 The present invention is based on a deep insight
35 into resonantly enhanced channel separation in the optical domain, and into the characteristics of Bragg gratings and how such grating work when provided in connec-

tion with a waveguiding structure. When a resonator is operatively connected to a waveguiding structure such as an optical fibre, a set of wavelength intervals will start to resonate in said resonator. Consequently, a high power level will build up inside the resonator, effectively filtering out the resonant wavelength(s). If attenuation is applied to a carefully selected portion of a waveguiding structure, comprising resonantly enhanced channel separation, attenuation will be provided predominantly to desired channels.

Channel balancing includes adjustment of the power level of one wavelength channel to a desired value. Thus, each channel within the WDM optical signal has an associated desired value. The desired value could be equal for all channels, in which case the channel balancing causes the power level of all channels to be equal. In other cases, the desired value could be set according to some predefined profile. Such profile, for example, could compensate for known losses in a transmission system before sending the optical signal (pre-equalisation of channels). The desired value could also be such that each channel exhibits the same signal-to-noise ratio, i.e. channels for which more noise is expected in the system are given a higher power level than those for which less noise is expected. Noise is introduced by, for example, amplifiers in the transmission system (such as amplified spontaneous emission in fibre amplifiers). Generally, the desired values could be set according to any input, including user input by means of a control console, the invention not being limited to any particular method for establishing the desired values.

In one aspect, the present invention provides a method for channel balancing of a WDM optical signal, by which method single wavelength channels can be attenuated separately. Channel separation according to the invention is achieved by providing a resonator that is resonant to at least one wavelength channel within said optical sig-

nal. The resonator establishes a region where the resonant channel has a substantially increased power density with respect to non-resonant wavelength channels. According to the invention, attenuation is provided in said region of increased power density. Attenuation is thus predominantly applied to the resonant channel, although the attenuation means *per se* might be non-discriminating in terms of wavelength.

In another aspect, the present invention provides an arrangement for channel balancing of a WDM optical signal. The arrangement comprises a spectrum analyser for analysing the power spectrum of the optical signal, and an attenuator for attenuating single wavelength channels within said optical signal. The arrangement further comprises a resonator that is resonant to at least one specific wavelength channel within the optical signal, and provides a selection region where a selected signal has a substantially increased power density in relation to channels out of resonance. Furthermore, the attenuator is arranged to attenuate said optical signal by acting upon or by adjusting the properties of the selection region. Thus, by providing a region where one channel within the optical signal is predominant, channel specific attenuation can be attained by using attenuation means that are essentially non-discriminating in terms of wavelength.

In another aspect, the present invention provides dynamic optical filters, or couplers, that can be arranged in cascade. The present invention provides optical filters that are both controllable in attenuation and tuneable in wavelength. One advantage of the present invention is that a plurality of filters can be tuned to approximately the same wavelength. By tuning more than one filter to wavelengths close to a selected wavelength channel, it is possible to shape the filtering. In other words, by superimposing the effects of a plurality of filters, the transmission of the filter can be tailored to a desired profile. For example, the transmission curve

of the filter can be flattened or broadened by allowing multiple filters to act on the same wavelength channel. In this way, a super dynamic capability can be achieved, further increasing the versatility of the channel balancing according to the present invention. Preferably, in order to achieve this super dynamic capability, a set of sub-resonators are associated with a common channel within the WDM signal.

In one embodiment, properties of the selection region are adjusted in order to change the phase of light in the selection region. By directing part of the power of the selected channel into the selection region, and leaving part of the channel in the optical signal, a phase change of the light in the selection region can cause destructive interference of the channel when it is fed back into the multiplexed signal. Consequently, the selected channel can be removed from the multiplexed optical signal by destructive interference. In fact, the destructive interference can be arbitrarily tuned by properly adjusting the phase of the singled-out portion, thereby allowing attenuation of the channel to any chosen degree. When attenuation is effected by means of destructive interference as described above, light is instead forced out of the selection region by making it impossible for the light to continue to propagate in the multiplexed optical signal.

Thus, according to one embodiment of the present invention, attenuation of one channel is achieved by dividing the power of said channel in two portions, and then adjusting the phase of one of said portions so that when the two portions are brought back together, destructive interference occurs in the propagation direction of the optical signal. More particularly, an arrangement for attenuation by destructive interference comprises a waveguiding structure, preferably an optical fibre, into which the wavelength division multiplexed optical signal is directed. In said fibre, there is provided a deflector

arranged to deflect light into an external resonator, said deflector preferably comprising a blazed, or tilted, phase grating. The external resonator can be tuneable in order to allow tuning of the wavelength to which said resonator is resonant. The deflector is weak, in that it only deflects a small fraction of light impinging thereupon. However, a strong field will quickly build up inside the resonator at the wavelength interval (or intervals) to which the resonator is resonant and thereby establish a selection region in which the power density of the resonant wavelength is considerably higher than of other wavelengths. Thus, at equilibrium, higher power will be reflected back and forth between the mirrors inside the external resonator, and the power deflected into the resonator from the fibre will be equal to the power deflected out from the resonator back into the optical fibre. By adjusting the phase of the light inside the external resonator, destructive interference between light from the resonator and light remaining in the fibre can be obtained in a selected propagation direction. Hence, by tuning the external resonator, it is possible to prevent light of the resonant wavelength from propagating in a selected direction in the fibre. Likewise, it is possible to achieve fractional destructive interference, and thereby prevent only a fraction of the resonant wavelength from propagating in a selected direction. In this way, tuneable attenuation of the channel power is attained. The features of this embodiment will be fully understood when the detailed description below is read.

30 In another embodiment, similar to the one described above, the external resonator is constantly tuned (or fixed) to provide constructive interference. According to this embodiment, attenuation is achieved by introducing a loss in the external resonator. Consequently, when the two portions of the channel are brought back together, the resulting power is lower than the power before divid-

ing the channel. Typically, it is possible to achieve up to about 50 percent attenuation with this embodiment.

According to yet another embodiment of the present invention, the external resonator encloses two optical
5 fibres. The selection region provided by said resonator is then responsible for the coupling of the resonant wavelength between said two fibres. The coupling factor between the two fibres can be tuned by adjusting the properties of the external resonator, and thereby provide
10 tuneable attenuation of the selected channel at the coupling between the two fibres. Alternatively, a variable loss can be introduced into the external resonator.

Other embodiments of the present invention rely on an internal resonator, rather than the external resonator
15 described above. The internal resonator is preferably co-linear with the propagation direction of the waveguiding structure. Such internal resonator is provided by arranging at least one Bragg grating in the waveguiding structure. Preferably, said grating is a chirped Bragg grating
20 being resonant to different wavelengths at different positions along the same. A controllable amount of power can easily be removed from one channel of the wavelength division multiplexed optical signal at the position of the corresponding resonance. Wavelength selective coupling assisted by a chirped Bragg grating is described in
25 the co-pending application "Optical Coupling" (US App. 09/608 218), which is hereby incorporated by reference.

According to the present invention, the internal resonance provides a selection region in which attenuation can be obtained by introducing, for example, a loss.
30 The loss can be of simple nature, for example a micro-bend of the fibre, said micro-bend causing light to leak out of the optical fibre. Since the power density of a selected channel in the selection region is substantially
35 higher than the power density of other channels, the loss predominantly affects the selected channel. Another feasible approach to achieve tuneable loss is to utilise

evanescent coupling of light from the selection region. By controlling the distance between a probe and the waveguiding structure, the power coupled out from the waveguiding structure can be controlled. Yet another
5 method of inducing a loss is to utilise controllable liquid crystals, in which the transmittance can be arbitrarily varied.

Preferably, the properties of the selection region are adjusted so that the selected channel is unaffected
10 in default setting. Furthermore, and since all channels except for the selected channel are unaffected by the selection region, any number of arrangements can be introduced in cascade in a communications network. Channel balancing according to the present invention is thus in-
15 herently cascadeable.

Furthermore, no feedback to the sender (the transmitter) is needed although pre-equalising is certainly possible within the scope of the present invention.

It is important to understand that the term channel
20 balancing does not imply that the power level of all channels should be made equal. Conversely, the power levels of the channels could be adjusted to any desired value. Thus, the present invention provides channel selective power control, thereby allowing control of the
25 power distribution between channels in a WDM or DWDM optical signal.

It is to be understood that all the embodiments of the present invention are inherently serial, in that any number of resonators (or selection regions) can be ar-
30 ranged in cascade. Thus, there is no limitation on the number of channels that can be balanced (i.e. individually attenuated).

Brief description of the drawings

35 In the following, a number of preferred embodiments of the present invention will be described in detail. The description below is more easily understood when read in

conjunction with the drawings, in which

figure 1 schematically shows an arrangement according to the present invention comprising external resonators;

5 figure 2 schematically shows an arrangement according to the present invention having a super dynamic capability;

figure 3 schematically shows a magnified picture of an arrangement according to the present invention;

10 figure 4 schematically shows an arrangement according to the present invention comprising external resonators in which controllable absorbers are provided;

figure 5 schematically shows an arrangement according to the present invention comprising controllable absorbers and having a super dynamic capability;

15 figure 6 schematically shows how a super dynamic filtering capability is achieved;

figure 7 schematically shows an input signal, a filter function and a filtered output signal;

20 figure 8 schematically shows, in block form, a set-up for channel balancing of an optical signal propagating in a fibre;

figure 9 schematically shows, in block form, a set-up for channel balancing, including a pre-amplifier and a power-amplifier for amplifying the optical signal;

25 figure 10 schematically shows an arrangement according to the present invention comprising two fibres provided within external resonators;

30 figure 11 schematically shows an arrangement according to the present invention comprising two fibres with internal resonators; and

figure 12 schematically shows two embodiments of an arrangement according to the present invention comprising a single fibre with internal resonators.

35 Throughout the drawings, like parts are designated by like references.

Detailed description of preferred embodiments

A first preferred embodiment of an arrangement according to the present invention is schematically shown in figure 1. The arrangement shown is to be regarded as the best mode of carrying out the invention, based on current knowledge.

Figure 1 shows a channel balancing arrangement having an input fibre 1 that is connected to an optical circulator 2. The circulator 2 is arranged to direct light coming from the input fibre 1 into an intermediate fibre 3, and to direct light coming from the intermediate fibre 3 into an output fibre 4. Channel balancing according to the present invention is accomplished in the intermediate fibre 3. The fibres 1, 3 and 4 are all capable of carrying a wavelength division multiplexed optical signal.

The intermediate fibre 3 comprises a chirped Bragg grating 5 (shown in the figures as vertical bars with increasing separation), which reflects all light within a predefined wavelength range back towards the circulator 2. The chirped grating 5 acts as a distributed back-reflector for light entering the intermediate fibre 3; different wavelengths are back-reflected at different positions of the chirped grating 5. Hence, if the intermediate fibre 3 is inactive, the optical signal will continue down the communications link on the output fibre 4 much as if the intermediate fibre 3 and the circulator 2 was not there.

However, at the intermediate fibre 3, there is arranged a plurality of external resonators 6, each of which is defined by a first 7 and a second 8 mirror arranged outside and on opposite sides of the fibre 3. Furthermore, each external resonator 6 is coupled to the intermediate fibre 3 by a respective deflector 9. The deflectors 9 are preferably comprised of tilted, i.e. blazed, Bragg gratings that are superimposed on the chirped Bragg grating 5 in the intermediate fibre 3, and

arranged to deflect light from the fibre 3 and into the respective external resonator 6, and to deflect light from each respective external resonator 6 into the fibre 3.

5 The deflecting power of the deflectors 9 can be very low, only a very small fraction of light in the fibre 3 being deflected into each external resonator 6. However, the chirped grating in the fibre governs, in the region where each wavelength is reflected, the accumulation of
10 power for that wavelength. Thus, the deflected power of any one wavelength can be enhanced by providing the deflector in the region where said wavelength is reflected by the chirped Bragg grating. At equilibrium, the coupling of light to and from the resonator will be equal.
15 The power of the resonant wavelength will be significantly increased inside the resonator, and will be coupled back into the intermediate fibre by the associated deflector. Note that since light is reflected back and forth in the resonators, the deflector (i.e. the tilted
20 Bragg grating) will couple light back into the fibre in both propagation directions. By making the refractive index modulation of the chirped grating 5 sufficiently large, a second resonance can be obtained in the chirped grating 5, which resonance further increases the coupling
25 of power of the resonant wavelength. The mechanism behind the resonantly enhanced coupling in connection with a chirped Bragg grating is comprehensively described in the aforementioned co-pending application "Optical Coupling" (US App. 09/608 218).

30 The part of the optical signal not entering any external cavity 6 will, as indicated above, be back-reflected by the chirped grating 5. At each deflector 9, the back-reflected light of one wavelength will interfere with light coupled out of the respective external resonator 6. By adjusting the external resonator, preferably by
35 a parallel displacement of the two mirrors 7 and 8 with respect to the fibre 3, destructive interference can be

achieved such that no light of the resonant wavelength can return to the optical circulator 2. Alternatively, destructive interference can be achieved by altering the optical path length of the external resonator by changing the refractive index in at least some portion thereof. Consequently, the corresponding wavelength channel is eliminated from the multiplexed optical signal. When light of one channel is prohibited to return to the circulator 2 in this way, light energy is instead forced to leave the system elsewhere, for example through the chirped grating 5 or through either of the resonator mirrors 7, 8.

It is to be understood that different levels of destructive interference can be obtained by adjusting the external resonators. This means that each channel can be fully blocked or fully passed, as well as partly blocked to any desired degree.

Hence, the external resonators provide selection regions where corresponding channels are singled-out from the multiplexed optical signal. Each of the external resonators 6 is individually adjustable so that, by cascading such resonators, attenuation can be effected simultaneously on any number of channels.

The arrangement shown in figure 1 is provided in an optical communications link, in which a WDM signal or a DWDM signal is propagated. The optical signal enters the optical circulator 2 from the input fibre 1; and is directed into the intermediate fibre 3 where the channel balancing is performed. From the intermediate fibre 3, light is directed into the output fibre 4 by the optical circulator 2 for further transmission down the communications link. Thus, the arrangement 10 is designed to be connected anywhere in an existing optical network.

An external resonator can also be tuned to be resonant to any wavelength within the tuning range by changing the separation between the first 7 and the second 8 mirror, or by tilting the external cavity 6 in its en-

tirety with respect to the fibre 3. In this way, more than one resonator can be made resonant to almost the same wavelength. Consequently, one channel within the multiplexed optical signal can be filtered (attenuated) by more than one selection region. This feature gives the arrangement according to the invention great versatility and provides a "super dynamic" capability, i.e. the capability of shaping the filter function. This super dynamic capability will be further described with reference to figure 2.

The variable attenuation by destructive interference will now be described in greater detail with reference to figure 3. Figure 3 is a schematic magnified picture of one external resonator 6 and its associated deflector 9. Also shown in the figure is the back-reflecting grating 5, now shown as a plane mirror in the waveguiding structure 3. The blazed grating, constituting the deflector 9, is shown as a single domain between the resonator mirrors. The above simplifications are for the purposes of graphical clarity only.

Light (the optical signal) is sent into the arrangement from the left in the figure, as indicated by the reference numeral 31. When impinging upon the deflector 9, some of the light is deflected towards the upper resonator mirror (as indicated by 32), and some light is transmitted towards the back-reflector (as indicated by 33). Light deflected towards the upper resonator mirror 32 is reflected back towards the deflector and, again, some light is reflected back to the left (as indicated by 34) in the figure (counter-propagating to the incoming light) and some light is transmitted towards the lower resonator mirror (as indicated by 35). Light initially transmitted towards the back-reflector 33 will, at the back-reflector 5, be reflected back towards the deflector 9. At the deflector, some of this light is reflected towards the lower resonator mirror (as indicated by 37), and some of the light is transmitted back to the left (as

indicated by 36) in the figure (counter-propagating to the incoming light).

Now, in the lower part of the external resonator 6a, two beams are superimposed; namely light from the back-reflector 37 and light from the upper resonator mirror 35. On the other hand, two beams are also superimposed in the waveguiding structure to the left of the deflector. For clarity only, the beams are shown with a small offset. By a parallel displacement of the external resonator 6 with respect to the waveguiding structure 3, or by changing the refractive index in at least some portion of the external resonator, destructive interference between the two superimposed beams can be obtained either in the lower part of the external resonator (beams 35 and 37), or in the waveguiding structure to the left of the deflector (beams 34 and 36). Consequently, if destructive interference is obtained in the waveguiding structure to the left of the deflector, all light is forced into the external resonator 6. The channel at issue is thus blocked from returning to the circulator 2 (not shown in figure 3). On the other hand, if destructive interference is obtained in the lower part of the external resonator 6a, light is actually prevented from entering the external resonator 6 at all, and hence all light is transmitted back towards the circulator 2. The channel at issue is thus unaffected and transmitted back to the circulator 2 in its entirety.

Figure 2 shows schematically an arrangement according to the present invention having a super dynamic capability. Each of the external resonators 6, as compared to the arrangement shown in figure 1, is divided into six separate external sub-resonators. It is to be understood that any number of sub-resonators is conceivable, the shown embodiment of six sub-resonators being an example only. In this embodiment, a wavelength division multiplexed optical signal coming into the optical circulator 2 from the input fibre 1 is directed into the intermedi-

ate fibre 3. In the intermediate fibre 3, separate channels of the optical signal are attenuated individually, i.e. channel balancing is performed. When it comes back to the optical circulator 2 from the intermediate fibre 3, the optical signal is directed into the output fibre 4 for further transmission down the optical communications link.

In the intermediate fibre 3, there is provided a chirped Bragg grating 5, reflecting essentially all light within a predefined wavelength range. Thus, if the optical signal is not manipulated within the intermediate fibre 3, the signal will return to the optical circulator 2 and be directed into the output fibre 4. At the intermediate fibre 3, there is arranged a plurality of external resonators 6, each of which comprises a plurality of sub-resonators. In fact, a sub-resonator is not different from any other external resonator, the expression sub-resonator being used only to point out that a plurality of resonators is coupled to, or associated with, a common channel within the optical signal. The external resonators 6 are coupled to the intermediate fibre 3 by deflectors superimposed on the chirped Bragg grating in the intermediate fibre. The deflectors are arranged to deflect light from the intermediate fibre 3 into the respective external resonator 6, and to deflect light from each external resonator 6 into the intermediate fibre 3.

The super dynamic capability of the arrangement shown in figure 2 is provided by the sub-resonators in each external resonator. As mentioned above, each external resonator is divided into a plurality of individual sub-resonators, each having its own phase and its own resonant wavelength. Each sub-resonator is defined by a pair of sub-mirrors, said sub-mirrors being individually controllable in order to allow tuning of the phase and the resonant wavelength of each sub-resonator individually. It is important to understand that when a plurality of external resonators is coupled to a common channel

within the optical signal, these external resonators are named sub-resonators (to that particular channel). Consequently, the effects of all sub-resonators are superimposed on each other when the resonant channels are deflected back into the intermediate fibre.

Although it could be possible to achieve a super dynamic capability with distributed resonators, each having its own deflector, it is preferred that the super dynamic capability for each channel is provided by a plurality of sub-resonators arranged adjacent to each other, and coupled to a common channel within the WDM or DWDM optical signal. With such an arrangement, the chirped grating that enhances the coupling between the external resonators and the intermediate fibre can be utilised effectively.

As illustrated in figure 6, each sub-resonator is adjusted to a different resonant wavelength and adjusted to provide a desired attenuation, thereby constituting, in fact, six different filters for the one and same channel. The superposition of these six filters provides the super dynamic capability of the arrangement shown in figure 2. By tuning the sub-resonators individually, the resulting filter function for a channel can be flattened, broadened or modified. The filtering is therefore said to be super dynamic, and the arrangement exhibits a super dynamic capability.

Referring now to figure 4, an embodiment related to that shown in figure 1 comprises controllable absorbers 12 or similar means inside the external resonators 6. In this case, the resonators need not be tuneable themselves as long as they are adjusted to the proper wavelength. Rather, controllable attenuation is provided by said absorbers 12. This embodiment is somewhat simpler than the foregoing, in that it lacks some of the features of the arrangement above. However, in many cases this less elaborated arrangement may be preferred by virtue of its simplicity.

The external resonators of the embodiment shown in figure 4 are typically arranged to provide constructive interference between back-reflected light from the chirped grating and light coupled out from the resonators. Attenuation is achieved by changing the amplitude of the light from the resonators. In an exemplary situation, half of the channel power could be deflected into the external resonator and half of the power could be back-reflected by the chirped grating. If no absorption takes place in the external resonator, the channel is not attenuated. On the other hand, if all light in the external resonator is absorbed, the channel power is halved. Thus, the embodiment of figure 4 could not, in the case indicated above, be used to eliminate a channel from the wavelength division multiplexed optical signal, but only to reduce the signal strength by half. However, in most practical applications, this is sufficient indeed.

The arrangement shown in figure 4 can be further extended to have super dynamic filtering capabilities, much alike the arrangement shown in figure 2, by using a plurality of external resonators as sub-resonators. An arrangement comprising external resonators arranged into sub-resonators and comprising a controllable absorber for each channel (each set of sub-resonators) is shown in figure 5. Although it is certainly possible to allow individual tuneability by adjustably mounting the sub-mirrors defining the sub-resonators, it is preferred to have fixed sub-mirrors. When the sub-mirrors are fixed, each sub-resonator is resonant to a fixed wavelength. The arrangement is only tuned by adjusting the transmittance of the controllable absorbers inside the external resonators. Further versatility is achieved by providing a dedicated absorber for each sub-resonator. Preferably, the absorber comprises an array of controllable liquid crystal cells. The transmittance of each cell then defines the attenuation in each sub-resonator.

The advantageous feature of super dynamic capability of the present invention is summarised in figure 6. As illustrated, more than one resonator is tuned to be resonant to a wavelength close to a selected channel. The resonant wavelength interval of each resonator is slightly overlapping, thereby providing a superposition of the filter curves, as indicated to the left in the figure. The total effect of in this case four different filters is indicated to the right of the figure. By superimposing a plurality of filters in this way, the transmission curve (the filter curve) can be tailored to a desired profile (shaped, flattened or broadened). Thus, this capability is referred to as being super dynamic. Arrangements having this super dynamic capability are described above and are schematically shown in figures 2 and 5.

Figure 7 shows schematically how channel balancing is performed. A plurality of channels within a wavelength division multiplexed optical signal is propagated in an optical fibre. The different channels have different signal powers, as indicated in the uppermost diagram of figure 7. The optical signal is launched into an arrangement for channel balancing according to the present invention. In the illustrated case, all channels are selected for attenuation and the desired result is that all channels should have the same power level (signal strength). For each of the channels, a resonance is established that provides a respective selection region. Each selection region is then adjusted so that proper attenuation D is applied to each channel. In other words, transmission windows are provided for each channel, as indicated in the centre diagram of figure 7. When the optical signal has passed through the transmission window (actually, when each channel has been attenuated by a desired amount), it is coupled into the transmission fibre carrying the signal (corresponding to the output fibre of the arrangement 10. Consequently, the optical signal has been

subject to channel balancing, in which the strength of all channels has been equalised, as indicated in the lowermost diagram of figure 7.

By using other levels of attenuation for each channel, it is straightforward to achieve any power profile of the balanced signal.

Figure 8 illustrates how channel balancing according to the present invention is implemented at an optical communications link. An attenuator arrangement 10 according to any one of the embodiments of the present invention is connected to an optical fibre 40 capable of carrying a wavelength division multiplexed optical signal. A controller 41 is operatively connected to the attenuating arrangement 10 in order to control the channel balancing. Downstream and/or upstream in the fibre 40 from the attenuating arrangement 10 there is provided a spectrum analyser 42. The spectrum analyser 42 is arranged to analyse the power spectrum of the optical signal propagating in the optical fibre 40. The measured power spectrum is sent to the controller 41 and at least one channel within the optical signal having higher than a desired power level is identified and selected for attenuation. The controller 41 adjusts the attenuating arrangement 10 in order to provide the desired attenuation of the at least one selected channel.

Either of the spectrum analysers 42 can be omitted. If spectrum analysis is performed only upstream from the attenuating arrangement, the optical signal is analysed prior to being subjected to attenuation, and the desired channel balancing is performed at the attenuating arrangement in accordance with the measured power spectrum forwarded to the controller. If, on the other hand, spectrum analysis is performed only downstream from the attenuating arrangement, the optical signal is analysed after being subjected to attenuation, and the measured power spectrum is fed back to the controller in order to provide the required channel balancing.

However, it is sometimes preferred to analyse the power spectrum of the optical signal both upstream and downstream of the attenuating arrangement. In this case, the measurement of the power spectrum performed upstream
5 from the attenuating arrangement is used to establish a desired attenuation, and the measurement performed downstream of the attenuating arrangement is used to check that the desired channel balancing was actually provided. It is to be understood that the spectrum analysis can be
10 performed remote from the attenuating arrangement 10, i.e. from the place where the actual channel balancing is performed. Nevertheless, it is preferred that spectrum analysis is performed close to the channel balancing, in order to minimise the need for feedback and feedforward
15 connections.

Furthermore, the controller 41 is preferably operatively connected to input 43 and output 44 devices, such as a keyboard, a peripheral monitoring and surveillance system, a display screen, etc., in order to allow auto-
20 mated or operator assisted control of the channel balancing. For example, it may be desired to reconfigure the controller 41 in order to provide channel balancing according to a new scheme. At one instant it may be preferred to achieve a uniform signal-to-noise ratio of the
25 channels in the optical signal; at some other instant it may be preferred to achieve a uniform power distribution; and at yet another instant it may be preferred to achieve a certain power profile.

Figure 9 shows schematically an extended implementation of the arrangement for channel balancing, including
30 a pre amplifier 45 upstream from the attenuator 10, and a power amplifier 46 downstream from the attenuator 10. Such configuration is often preferred in order to achieve a high enough power level of the channels. The amplifiers
35 45, 46 can have a predefined gain, but it is also conceivable to control the gain of the amplifiers from the controller 41.

Figure 10 shows schematically yet another embodiment of an attenuating arrangement according to the present invention. In this case, two fibres 101, 102 are enclosed within external resonators 6. Rather than coupling the resonant channel back into the same fibre from the selection region, as is the case for the arrangement shown in figure 1, the selected channel is coupled into a second intermediate fibre 101. Similar to the arrangement shown in figure 1, the arrangement of figure 10 can be provided with chirped Bragg gratings (not shown) in the intermediate fibres 101, 102 as well as with controllable absorbers 12 in the external resonators 6. An advantage of this embodiment is that the optical circulator can be eliminated by connecting an input fibre from the optical communications link to one of the intermediate fibres, and an output fibre to the other of the intermediate fibres.

Figure 11 shows schematically another embodiment of an attenuating arrangement according to the present invention. The embodiment shown in figure 11 is different from the one shown in figure 9 in that the external resonators are omitted. In this case, instead, internal resonators are utilised, which are constituted by a chirped Bragg grating 5 of strong index modulation in each fibre. Attenuation of an individual channel is easily achieved by introducing an absorber 12 between the two fibres. One channel is deflected from one fibre to the other by deflectors 9 superimposed on the chirped Bragg grating in the two fibres. Although the resolution of a filter according to the embodiment shown may not be as good as for the embodiment of figure 10, it may still be preferred by virtue of its simplicity.

Figure 12 shows schematically an ingeniously simple embodiment of the present invention. In this case, a chirped grating 5 inside the fibre provides resonances to different wavelengths at different positions along the same. These resonances define a number of selection regions, in which the resonant wavelength has a substan-

tially higher power density than other wavelengths. Wavelength specific (i.e. channel specific) attenuation is obtained by acting upon the fibre at the proper positions. For example, a loss can be introduced simply by pressing on the fibre at the appropriate position (at the position in which the chirped grating is resonant to the desired channel) and thus induce micro-bends that cause leaking of light out from the fibre, as shown in the lower picture of figure 12. By pressing on the fibre at a proper selection region, loss is predominantly introduced for the selected channel in that region (i.e. the channel that is resonant in said region).

Note that the power density of the resonant wavelength is increased in the selection region. This allows of a small enough loss to be used not to affect other wavelengths (other channels).

Alternatively, the loss can be introduced by moving a probe close to the waveguiding structure, thereby causing evanescent coupling of light out from the same, as shown in the upper picture of figure 12. The amount of light coupled out depends on the separation of the probe from the waveguiding structure. Preferably, if evanescent coupling is used for attenuating the optical signal, the cladding of fibre is partly removed in order to allow evanescent interaction with light in the core of the fibre.

It is to be understood that each resonator or resonant portion in the attenuating arrangement is, in fact, a dynamic optical coupler. The dynamic optical coupler can be utilised to remove a controlled amount of power from the resonant wavelength channel. For example, the dynamic optical coupler can be used as an add/drop device for adding and/or dropping a selected channel to or from a wavelength division multiplexed optical signal propagating in an optical fibre.

Optical fibres that are commonly used for communication purposes are usually not polarisation maintaining.

Therefore, it is preferred, and in some cases essential, that the channel specific power control according to the present invention is performed on two orthogonal polarisation directions. It is preferred, for example, that the WDM optical signal is separated into two orthogonal polarisation components and sent into a respective polarisation maintaining fibre, in which channel selective power control (or channel balancing) according to the present invention is performed on both components separately and in concert. Subsequently, the two components are recombined into the transport fibre (which is typically not polarisation maintaining) after having been subject to said power control.

The embodiments of the present invention that are described above and schematically shown in the drawings are not intended to limit the scope of the protection sought. On the contrary, any person skilled in the art will realise that a number of different embodiments, and modification of the embodiments shown and described, are conceivable within the scope of the invention. The scope of the invention is defined in the appended claims.

CLAIMS

1. A method for channel selective power control of a wavelength division multiplexed optical signal, the
5 method including the steps of:
 selecting at least one channel within said optical signal having higher than a desired power level;
 establishing a resonance to the selected channel,
the resonance providing a selection region where said se-
10 lected channel has a substantially increased power density relative to channels out of resonance; and
 attenuating said selected channel a desired amount by adjusting the properties of said selection region.
- 15 2. A method as set forth in claim 1, in which the step of selecting at least one channel having higher than a desired power level is performed by means of spectrum analysis of the wavelength division multiplexed optical signal.
- 20 3. A method as set forth in claim 1, in which the step of establishing a resonance comprises the steps of
 providing an external resonator, which is defined by a first and a second mirror, said first and said second
25 mirror being provided outside and on opposite sides of a waveguiding structure, preferably an optical fibre, carrying the optical signal; and
 deflecting light between the waveguiding structure and the external resonator, said deflecting being ef-
30 fected by a deflector provided in said waveguiding structure.
4. A method as set forth in claim 1, in which the step of attenuating is performed by introducing a loss in the
35 selection region.

5. A method as set forth in claim 4, in which the step of attenuating is performed by introducing an absorbing element in the selection region.
- 5 6. A method as set forth in claim 3, in which the step of attenuating is performed by introducing an absorbing element inside the external resonator.
7. A method as set forth in claim 4, in which the step
10 of attenuating is performed by making the selection region leaky, light thereby being caused to leak out of the same.
8. A method as set forth in claim 3, in which the step
15 of attenuating is performed by changing the phase of the selected channel in the selection region relative to the phase of the selected channel in the waveguiding structure, thereby causing destructive interference on the selected channel.
- 20 9. A method as set forth in claim 8, in which the phase of the selected channel is changed by making a parallel displacement of the first and the second mirror with respect to the waveguiding structure.
- 25 10. A method as set forth in claim 8, in which the phase of the selected channel is changed by altering the refractive index in at least some portion of the external resonator, thereby altering the optical path length in
30 the resonator.
11. A method as set forth in claim 9 or 10, further comprising the step of altering the separation between the first and the second mirror.
- 35 12. A method as set forth in claim 1, further comprising the steps of

deflecting the selected channel from a first waveguiding structure carrying the optical signal into an external selection region; and

coupling the selected channel from the selection re-
5 gion into a second waveguiding structure;

the step of attenuating the selected channel being performed by absorbing light in said selection region.

13. A method as set forth in claim 12, in which the step
10 of establishing a resonance comprises the step of providing an external resonator enclosing both the first and the second waveguiding structures, said external resonator being defined by a first and a second mirror arranged outside and on opposite sides of the first and the second
15 waveguiding structures.

14. A method as set forth in claim 12, in which the step of establishing a resonance comprises the step of providing at least one Bragg grating in each of the first and
20 the second waveguiding structures.

15. A method as set forth in claim 14, in which at least one of the Bragg gratings is a chirped grating.

25 16. A method as set forth in any one of the claims 12 to 15, in which the step of deflecting the selected channel from the first waveguiding structure is performed by means of a first blazed phase grating in the first waveguiding structure, and the step of coupling the se-
30 lected channel into the second waveguiding structure is performed by means of a second blazed grating in the second waveguiding structure.

17. A method as set forth in claim 1, in which the resonance to the selected channel is established by arranging
35 one or several Bragg gratings inside a waveguiding struc-

ture, preferably an optical fibre, carrying the optical signal.

18. A method as set forth in claim 17, in which the
5 resonance is established by arranging a chirped Bragg grating in the waveguiding structure, said grating being resonant to different wavelength channels at different portions along the same.

10 19. A method as set forth in claim 18, in which the selection region is comprised within the resonance, and attenuation is provided by introducing a loss in said selection region.

15 20. A method as set forth in claim 19, in which the selection region is made leaky by bending a selected portion of the waveguiding structure, light of predominantly the selected channel thereby being caused to leak out from the selection region.

20 21. A method as set forth in claim 19, in which the selection region is made leaky by moving a light guiding probe close enough to the waveguiding structure to allow evanescent coupling of light from the waveguiding structure into said probe.
25

22. A method as set forth in claim 3, in which the deflector is provided within an internal resonator in the waveguiding structure, thereby enhancing the spectral selectivity of the channel balancing.
30

23. A method as set forth in claim 3, further comprising the step of tuning the external resonator to the wavelength of the selected channel.
35

24. A method as set forth in claim 23, in which the step of tuning the resonance is performed by adjusting the separation between the first and the second mirror.
- 5 25. A method as set forth in claim 23, in which the step of tuning the resonance is performed by tilting the external resonator with respect to the waveguiding structure.
- 10 26. A method as set forth in claim 23, in which the step of tuning the resonance is performed by
adjusting the separation between the first and the second mirror; and
tilting the external resonator with respect to the
15 waveguiding structure.
27. A method for controlled removal of power from a selected channel within a wavelength division multiplexed optical signal propagating in a waveguiding structure,
20 preferably an optical fibre, comprising the steps of:
establishing a selection region in which the power density of said selected channel is increased relative to other channels within said optical signal; and
removing a controlled amount of power from said se-
25 lected channel by controlling the properties of said selection region.
28. A method as set forth in claim 27, in which a channel is selected by performing spectrum analysis of the
30 wavelength division multiplexed optical signal, and selecting at least one channel having higher than a desired power level.
29. A method as set forth in claim 27, in which the step
35 of establishing a selection region comprises the step of providing a resonance to the selected channel, in which

resonance the power density of the selected channel is increased relative to other channels.

30. A method as set forth in claim 29, in which the selection region is established outside the resonance.

31. A method as set forth in claim 29, in which the selection region is established within the resonance.

32. A method as set forth in claim 27, in which the step of removing a controlled amount of power from the selected channel is performed by introducing a variable loss in the selection region.

33. A method as set forth in claim 32, in which the variable loss is introduced by absorbing a controlled amount of light in the selection region.

34. A method as set forth in claim 27, in which a controlled amount of power is removed by adjusting the properties of the selection region in such a way that destructive interference is achieved, which prevents light from propagating in the waveguiding structure.

35. An arrangement for channel selective power control of a wavelength division multiplexed optical signal propagating in a waveguiding structure, preferably an optical fibre, the arrangement comprising

a spectrum analyser arranged to analyse the power spectrum of said optical signal and to identify and select at least one channel within said optical signal having higher than a desired power level;

an attenuator arranged to attenuate a selected channel within said optical signal; and

a resonator arranged to provide a selection region where the selected channel has a substantially increased power density relative to channels out of resonance,

the attenuator further being arranged to attenuate said selected channel by changing the properties of said selection region.

5 36. An arrangement as set forth in claim 35, comprising a plurality of attenuators and a plurality of resonators, said attenuators and said resonators being arranged to attenuate a plurality of wavelength channels within a wavelength division multiplexed optical signal.

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37. An arrangement as set forth in claim 35, further comprising a controller, said controller being arranged to receive, from the spectrum analyser, information identifying the at least one channel having higher than a desired power level, and to control the attenuator to provide a desired level of attenuation to said at least one channel.

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38. An arrangement as set forth in claim 37, wherein the spectrum analyser is operatively connected to the optical fibre upstream from the attenuator.

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39. An arrangement as set forth in claim 37, wherein the spectrum analyser is operatively connected to the optical fibre downstream from the attenuator.

25

40. An arrangement as set forth in claim 38, wherein a second spectrum analyser is operatively connected to the optical fibre downstream from the attenuator, said second spectrum analyser also being operatively connected to the controller.

30

41. An arrangement as set forth in claim 35, wherein the resonator is an internal resonator arranged in the waveguiding structure, said internal resonator comprising a chirped Bragg grating.

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42. An arrangement as set forth in claim 35, wherein the resonator is an external resonator arranged outside the waveguiding structure, said external resonator being defined by two mirrors arranged outside and on opposite
5 sides of the waveguiding structure, said external resonator being coupled to said waveguiding structure by a deflector.

43. An arrangement as set forth in claim 42, wherein the
10 attenuator is arranged to introduce a loss in the selection region.

44. An arrangement as set forth in claim 42, wherein the attenuator is arranged to change the properties of the
15 selection region in such a way that the phase of light being coupled back into the waveguiding structure from the external resonator is out of phase with light of the resonant wavelength propagating in the waveguiding structure, thereby causing attenuation by destructive interference.
20

45. An arrangement as set forth in claim 42, wherein a plurality of external resonators is coupled to a common channel of the WDM signal, said plurality of external
25 resonators thereby constituting a set of sub-resonators associated with said channel.

46. An arrangement as set forth in claim 42, wherein the external resonator is adjustable in such way that the
30 wavelength to which the external resonator is resonant can be tuned.

47. An optical device, comprising
a waveguide, preferably an optical fibre, capable of
35 carrying an optical signal having a plurality of wavelength channels;
a resonator operatively connected to said waveguide,

the resonator being resonant to at least one wavelength interval within said plurality of wavelength channels, said resonator establishing a region where the resonant wavelength interval has a substantially increased power density relative to wavelength intervals out of resonance; and

a controller arranged to adjust said resonator such that a controlled amount of power is removed from the resonant wavelength.

10

48. A device as set forth in claim 47, wherein the resonator is controllable such that the wavelength interval to which the resonator is resonant can be tuned, thereby allowing removal of power from different wavelength intervals at different instants.

15

49. A device as set forth in claim 47, wherein the resonator is an external resonator arranged outside the waveguide, said external resonator being defined by two mirrors arranged outside and on opposite sides of the waveguide, said external resonator being coupled to said waveguide by a deflector.

20

50. A device as set forth in claim 49, wherein the deflector comprises a blazed phase grating provided in a core of the waveguide.

25

51. A device as set forth in claim 49, wherein the controller is operative to change the phase of light of the resonant wavelength in the resonator relative to the phase of light of the same wavelength in the waveguide, thereby causing destructive interference on said wavelength.

30

52. A device as set forth in claim 51, wherein the controller is operative to change the phase of light in the

35

resonator by causing a parallel displacement of the external resonator with respect to the waveguide.

53. A device as set forth in claim 51, wherein the controller is operative to change the phase of light in the resonator by causing a change in the refractive index in at least some portion of the external resonator.

54. A device as set forth in claim 49, wherein the controller is operative to provide absorption in the external resonator.

55. A device as set forth in claim 54, further comprising a controllable liquid crystal provided inside the external resonator, the controller being operative to provide absorption by changing the transmittance of said liquid crystal.

56. A device as set forth in claim 47, wherein the resonator is an internal resonator arranged inside the waveguide, said internal resonator comprising at least one Bragg grating.

57. A device as set forth in claim 56, wherein the resonator comprises a chirped Bragg grating.

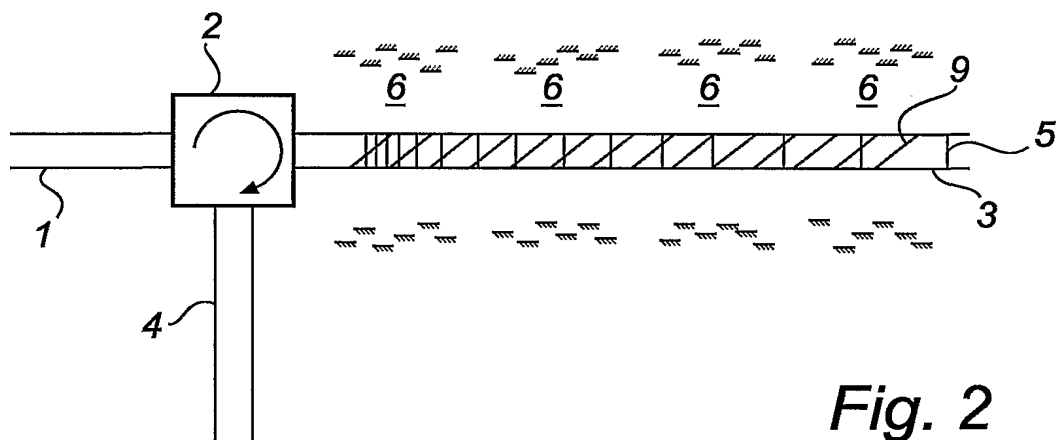
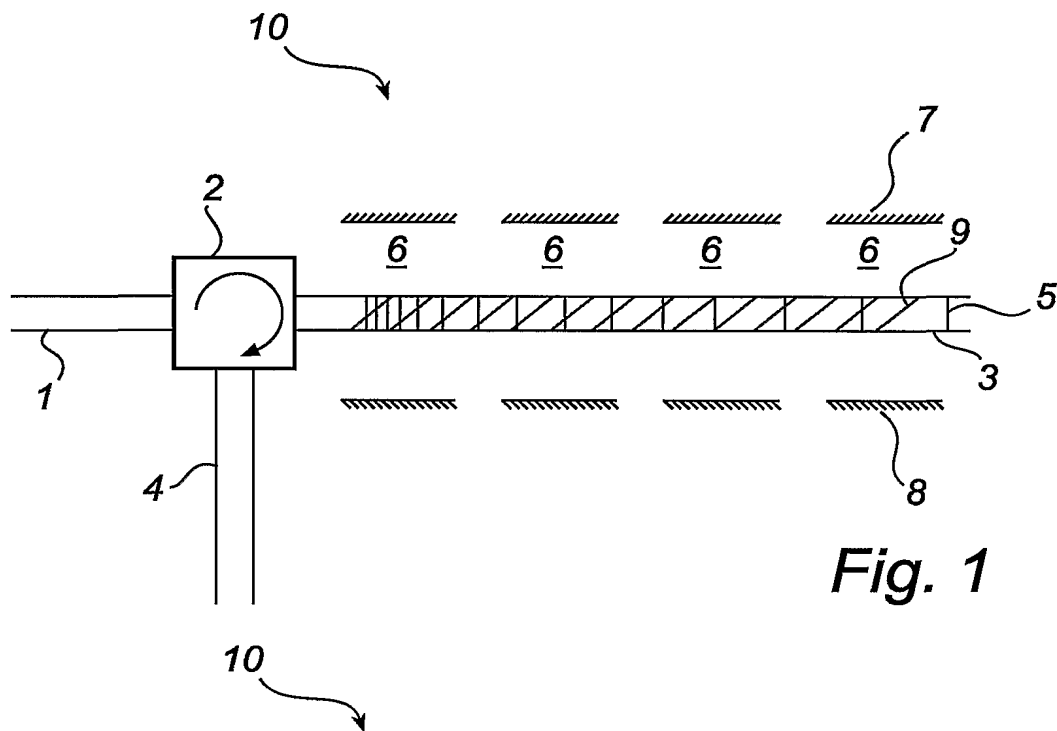
58. A device as set forth in claim 56 or 57, wherein the waveguide comprises a bend that makes the resonator leaky.

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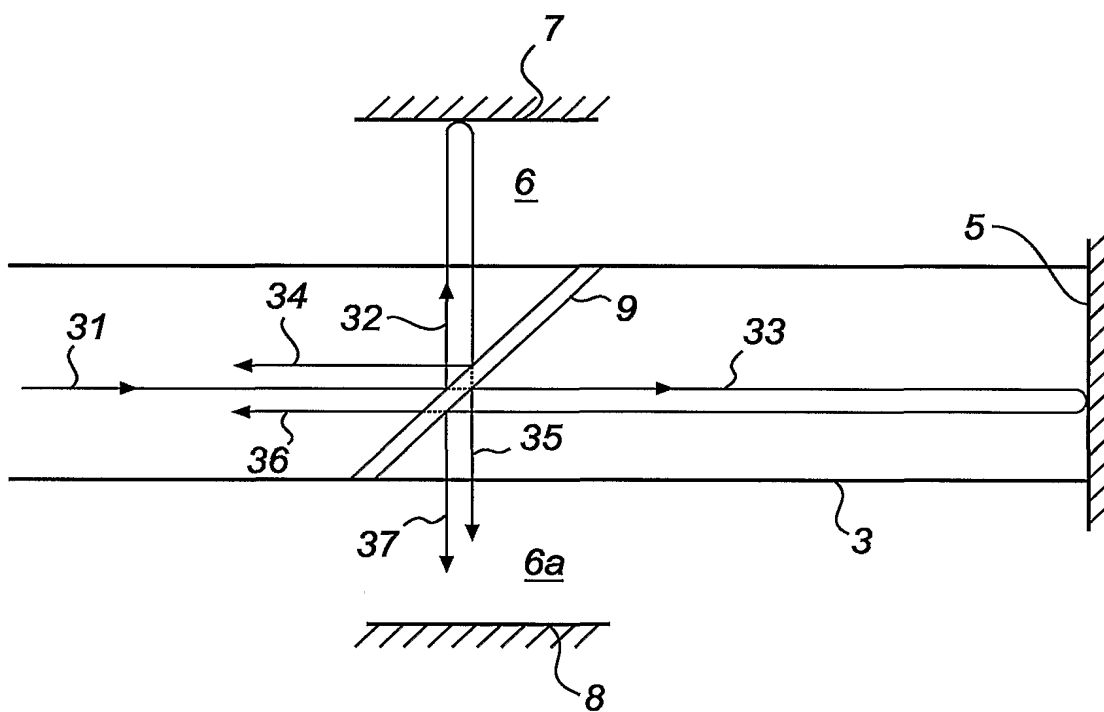
59. A device as set forth in claim 56 or 57, wherein a light guiding probe is arranged within evanescent contact with the waveguide, light thereby leaking out from the resonator to said probe.

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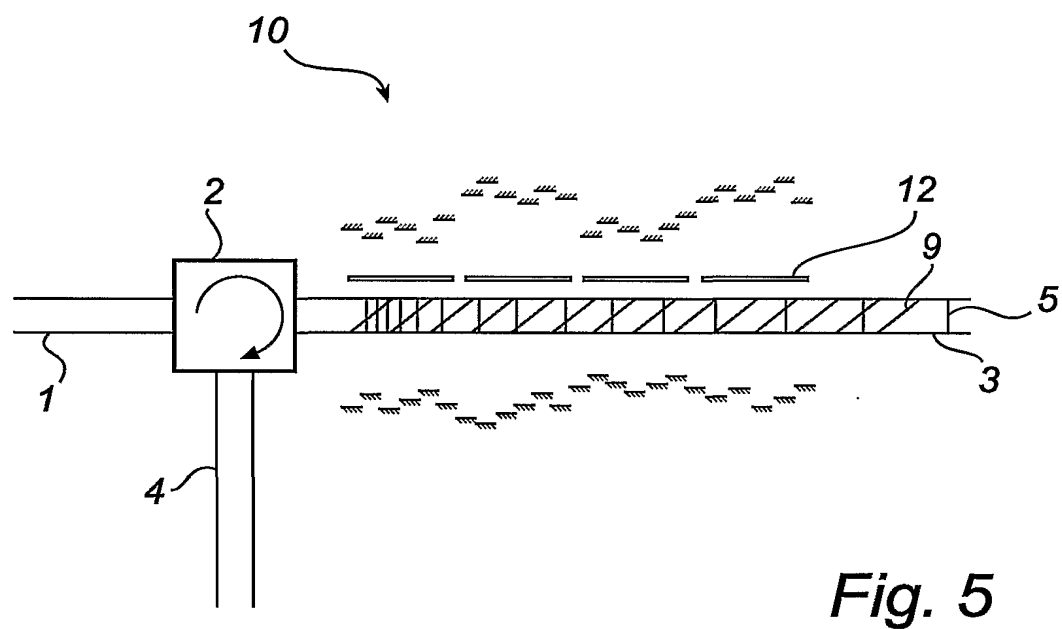
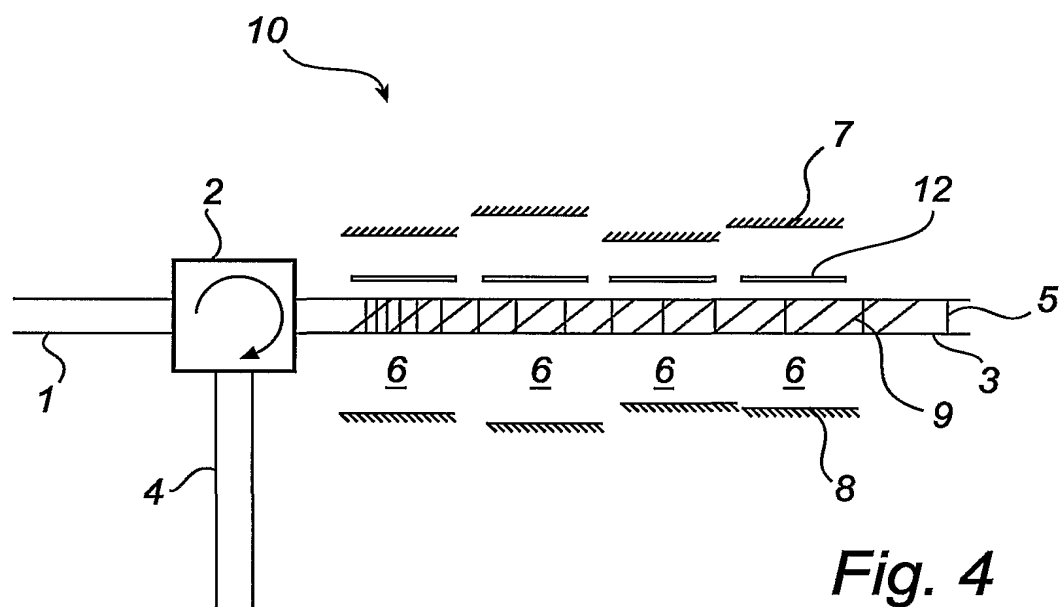
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*Fig. 3*

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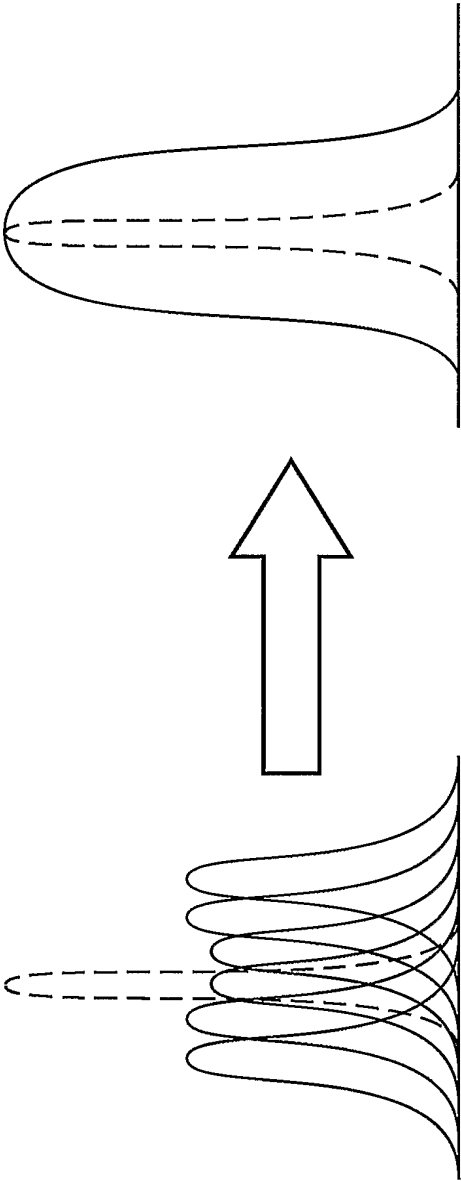


Fig. 6

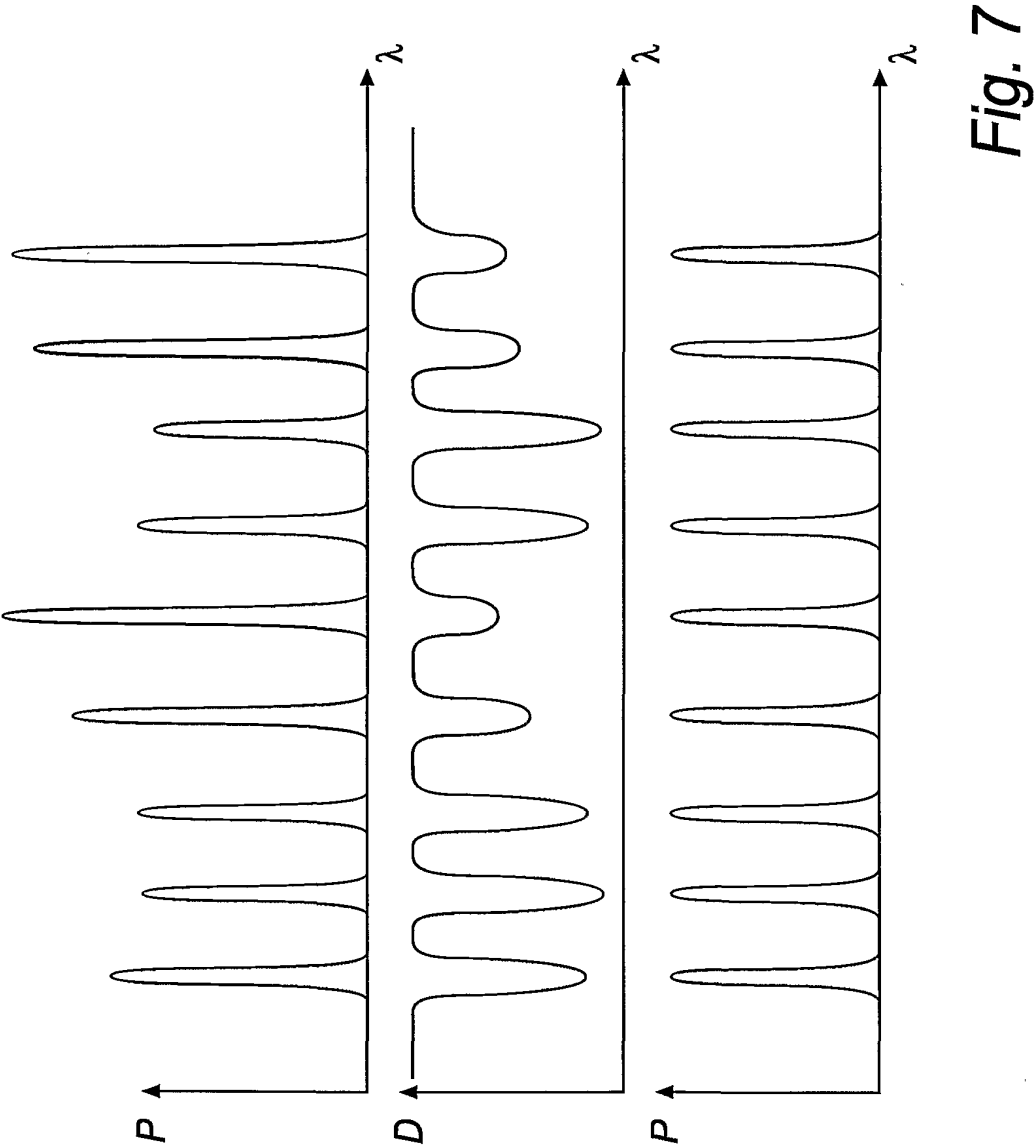


Fig. 7

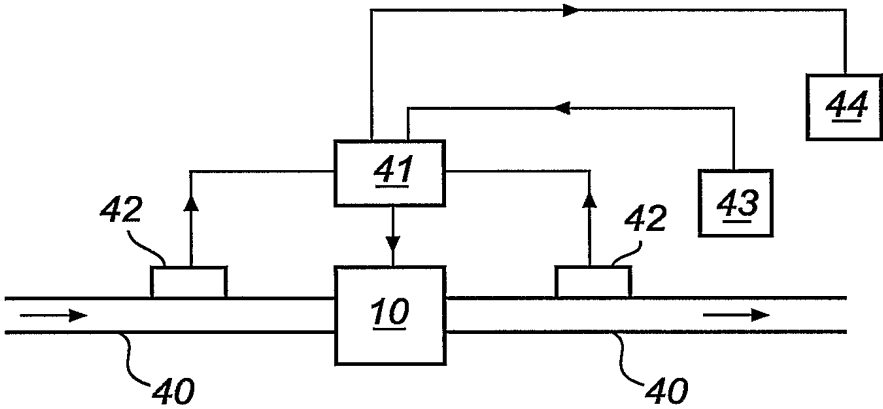


Fig. 8

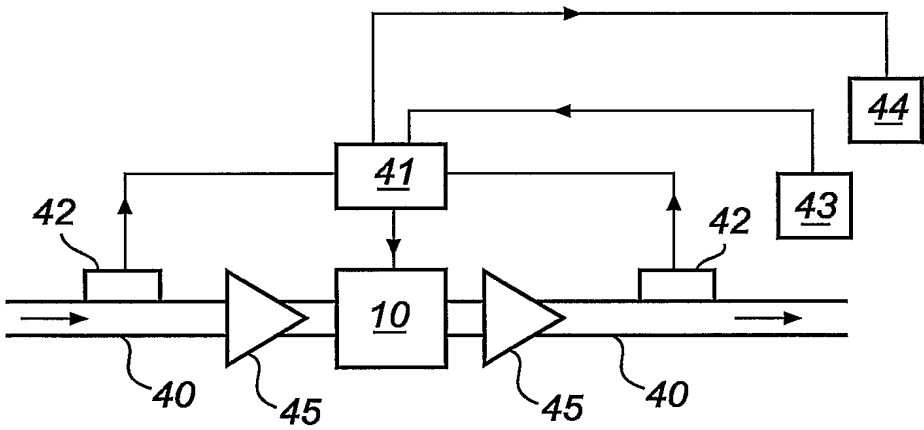
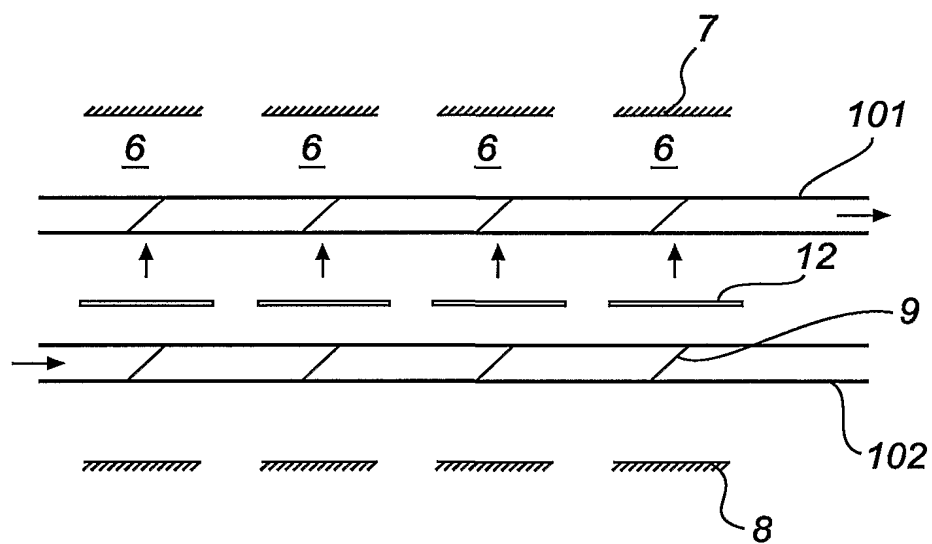
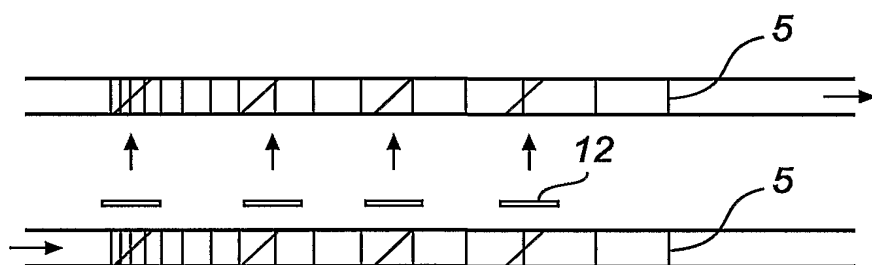


Fig. 9

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*Fig. 10**Fig. 11*

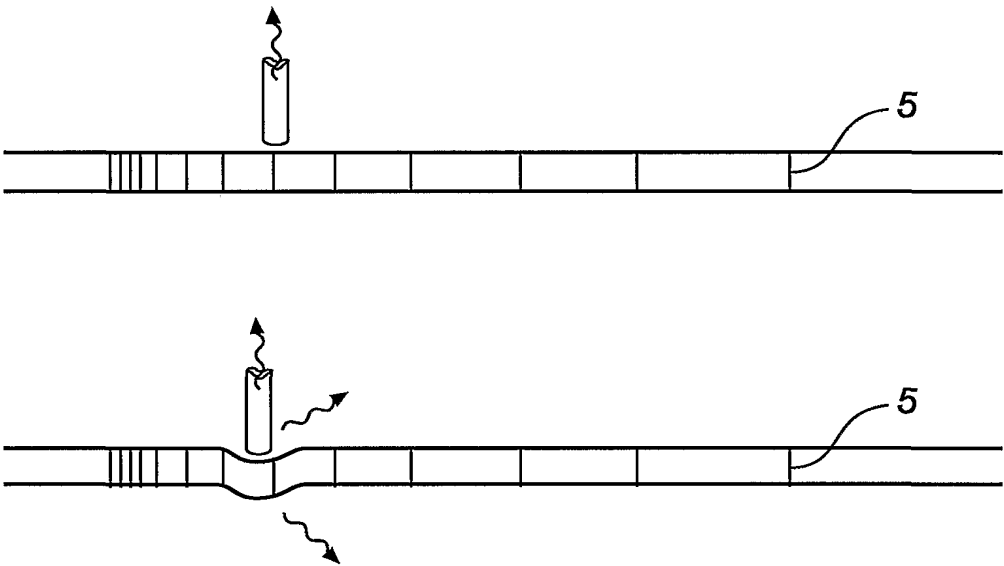


Fig. 12

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SE 01/02840

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: H04J 14/02, H04B 10/17

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: H04J, H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	US 5093876 A (HENRY,C.H.ET AL), 3 March 1992 (03.03.92), abstract --	1-59
A	WO 9900924 A1 (UNIPHASE TELECOMMUNICATIONS PRODUCTS,INC.), 7 January 1999 (07.01.99), abstract -- -----	1-59

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

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Date of the actual completion of the international search

9 April 2002

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/SE 01/02840

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